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13. ABSTRACT *(Maximum 200 words)*

In this report we summarize our research on ionospheric plasma turbulence and effects on radio waves as well as laboratory simulations, conducted at Arecibo, Puerto Rico and at MIT campus. Large-scale plasma turbulence can be generated in the ionosphere by injected HF radio waves , to appear in the forms of various plasma waves (e.g., Langmuir waves, ion acoustic waves, lower hybrid waves, upper hybrid waves etc.), sheet-like plasma density irregularities, depleted magnetic flux tubes, and plasma bubbles. This research has advanced physics of nonlinear electromagnetic wave interactions with magnetized plasmas. Although plasma density irregularity and depleted magnetic flux tubes are locally produced by the injected HF radio waves, they can extend along the Earth's magnetic fields to a large distance, to establish artificial ionospheric ducts for controlled radio wave communications paths. Detailed reports of these research results are given in the listed journal articles.

14. SUBJECT TERMS

ionospheric plasma bubbles, large-scale sheet-like plasma irregularities, depleted magnetic flux tubes, ionospheric plasma turbulence

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Final Report for Research Sponsored by AFOSR Grant F49620-98-0389
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Under the sponsorship of AFOSR, we have investigated radio wave-induced ionospheric plasma turbulence both experimentally and theoretically. Our HF wave injection experiments at Arecibo, Puerto Rico [Lee et al., 1997; Lee et al., 1998(a); Lee et al., 1998(b); Lee et al., 1999; Starks and Lee, 2000; Starks et al., 2001] and laboratory simulations on MIT campus [Lee et al., 1997; Lee et al., 1998(c)] have advanced physics of nonlinear electromagnetic (EM) wave interactions with magnetized plasmas. Fascinating phenomena, such as the generation of Langmuir wave turbulence [Lee et al., 1997; Lee et al., 1998(c)], plasma bubbles [Lee et al., 1998(a)], sheet-like plasma density irregularities [Lee et al., 1998(b)], and augmentation of naturally-occurring plasma turbulence [Lee et al., 1999], were discovered or corroborated under the guidance of our earlier theoretical and experimental studies [Lee and Kuo,1983; Lee and Kuo, 1985; Kuo and Lee, 1992; Lee et al., 1992].

Strong EM wave-plasma interactions occur in the F-region, especially, near the reflection height of vertically injected HF heater waves. Short-scale plasma modes can be excited by various parametric instabilities, as observed in our field experiments at Arecibo [e.g., Lee et al., 1997] and simulated in our Versatile Toroidal Facility (VTF) laboratory experiments [Lee et al., 1997; Lee et al., 1998(c)] at the Plasma Science and Fusion Center. The Versatile Toroidal Facility (VTF) is a large plasma machine constructed by MIT's graduate and undergraduate students, under the joint sponsorship of the Air Force of Scientific Research and MIT Undergraduate Research Opportunity Program (UROP) Office.

Large-scale sheet-like plasma irregularities [Lee et al., 1998(c)] and depleted magnetic flux tube [Lee et al., 1999] are generated by the thermal filamentation instabilities [Lee and Kuo, 1985] and thermal-effect-induced chemical reactions, respectively. Although irregularity sheets and depleted flux tubes are ``locally" produced by the injected HF waves, they can extend along the Earth's magnetic field to a large distance, to establish artificial ionospheric ducts for controlled radio communications purposes [Lee et al., 1992; Starks and Lee, 2000; Starks et al., 2001]. These research results are

reported and the support by the AFOSR grant F49620-98-0389 is acknowledged in the following journal articles:

(1) Kuo, S.P., M.C. Lee, P.A. Kossey, K.M. Groves, and J.A. Heckscher, Stimulated thermal instability for ELF and VLF wave generation in the Polar electrojet, Geophysical Research Letters, 27, 85, 2000.

(2) Lee, M.C. , R.J. Riddolls, K.D. Vilece, N.E. Dalrymple, M.J. Rowlands, D.T. Moriarty, K.M. Groves, M.P. Sulzer, and S.P. Kuo, Laboratory reproduction of Arecibo experimental results: HF wave-enhanced Langmuir waves, Geophysical Research Letters, 24, 115, 1997.

(3) Lee, M.C., R.J. Riddolls, W.J. Burke, M.P. Sulzer, E.M.C. Klien, M.J. Rowlands, and S.P. Kuo, Ionospheric plasma bubble generated by Arecibo heater, Geophysical Research Letters, 25, 579, 1998(a).

(4) Lee, M.C., R.J. Riddolls, and D.T. Moriarty, Laboratory studies of some ionospheric plasma effects caused by lightning induced whistler waves, Journal of Atmospheric and Solar-Terrestrial Physics, 60, 965, 1998(b).

(5) Lee, M.C., R.J. Riddolls, W.J. Burke, M.P. Sulzer, S.P. Kuo, and E.M.C. Klien, Generation of large sheet-like ionospheric plasma irregularities at Arecibo, Geophysical Research Letters, 25, 3067,1998(c).

(6) Lee, M.C., Y.R. Dalkir, and E.R. Williams, Radar reflectivity of lightning-induced plasmas, Journal of Atmospheric and Solar-Terrestrial Physics, 60, 941, 1998(d).

(7) Lee, M.C., E.M.C. Klien, W.J. Burke, A.X. Zhang, R.J. Riddolls, S.P. Kuo, M.P. Sulzer, and B. Isham, Augmentation of natural ionospheric plasma turbulence by HF heater waves, Geophysical Research Letters, 26, 37,1999.

(8) Starks, M.J. and M.C. Lee, Matched filtering for the measurement of conjugately ducted VLF transmissions, Radio Science, 35, 351, 2000.

(9) Starks, M.J., M.C. Lee, and P. Jastrzebski, Interhemispheric propagation of VLF transmissions in the presence of ionospheric HF heating, to be published in April 2001 issue of the Journal of Geophysical Research.

In addition, two M.S. theses and two Ph.D. dissertations were completed under the support of the AFOSR grant. They are

(1) Shaun L. Meredith, Construction of a gridded energy analyzer for measurements of ion energy distribution in the Versatile Toroidal Facility, Advisor: Min-Chang Lee, Department of Nuclear Engineering, Massachusetts Institute of Technology, 1998.

(2) Ryan J. Riddolls, Two-probe technique to measure wavenumber-frequency spectrum of VTF plasma, Advisor: Min-Chang Lee, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 1999.

(3) Michael J. Starks, Measurement of conjugate propagation of VLF waves by matched filter and application to ionospheric diagnosis, Advisor: Min-Chang Lee, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 1999.

(4) Nathan E. Dalrymple, Simulation of ionospheric plasma heating experiments in the Versatile Toroidal Facility, Advisor: Min-Chang Lee, Department of Nuclear Engineering, Massachusetts Institute of Technology, 2001.